

Mass Profiles and Shapes of Cosmological Structures
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ELLIPTICAL GALAXY HALO MASSES FROM INTERNAL KINEMATICS

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Abstract. The halo masses of nearby individual elliptical galaxies can be estimated by using the kinematics of their stars, planetary nebulae, and globular clusters—ideally in combination. With currently improving coverage of galaxies of ordinary luminosities and morphologies, systematic trends may be identified. Bright, boxy ellipticals show strong signatures of dark matter, while faint, disky ones typically do not. The former result is problematic for the MOND theory of gravity, and the latter is a challenge to explain in the Λ CDM paradigm of galaxy formation.

1 Introduction

While the mass profiles of spiral galaxies can be studied via their extended cold gas disks, elliptical galaxies rarely offer this avenue. An obvious alternative is to measure the kinematics of the integrated stellar light, but this is observationally prohibitive in the low surface brightness outer regions where the mass profile is of the most interest. Even when the kinematics are measured, interpretation is more difficult than in spirals because of uncertainties in the intrinsic shapes, viewing angles, and orbit types. Additional complications are dust effects (Baes & Dejonghe 2001) and stellar population bias (De Bruyne et al. 2004).

It is possible to surmount many of the obstacles to interpretation with sufficient data and sophisticated models. The orbit types can be determined using higher order moments of the velocity distribution (van der Marel & Franx 1993), and the shapes and viewing angles can be constrained using integral field data (Cappellari et al. 2005 = C+05). It remains to be seen if all the degeneracies can be removed when only 3 of the 6 phase space dimensions are probed. In any case, there has until now been no systematic survey of individual nearby elliptical galaxies which includes an unbiased sample, extended data, and adequate models—and thus general conclusions about their dark matter halos should be considered tentative.

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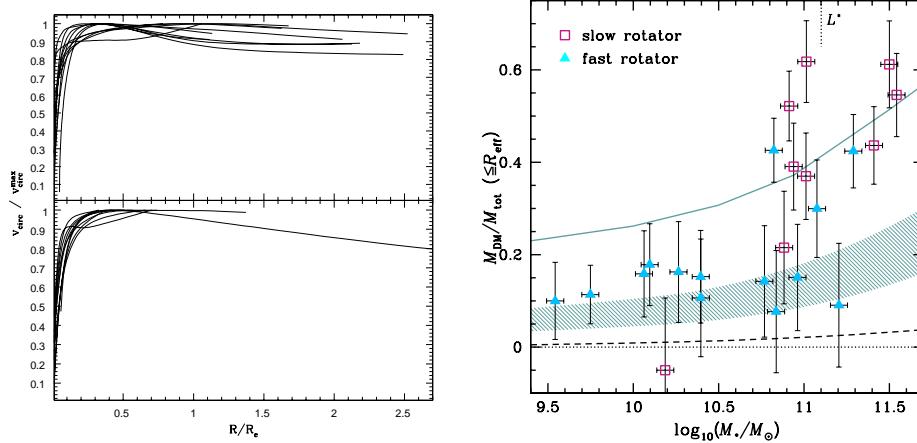


Fig. 1. *Left:* Rescaled circular velocity profiles of elliptical galaxy sample from G+01. *Right:* Central dark matter fraction in SAURON sample of ellipticals. The shaded region shows the 1- σ range with dissipationless Λ CDM halos included. The solid line illustrates the effects of adiabatic contraction. The dashed line shows the MOND prediction.

2 Results from integrated stellar kinematics

While there have been many studies of stellar kinematics in ellipticals, so far the most reliable survey for dark matter (DM) was from Kronawitter et al. (2000) and Gerhard et al. (2001 = G+01). With long-slit data on 21 bright, round ellipticals, they found that the circular velocity $v_c(r)$ is roughly constant to $1-2 R_{\text{eff}}$ (5–10 kpc; see Fig. 1, left). Statistically, the central DM density appeared to be 25 times larger in ellipticals than in spirals. But on an individual basis, a constant mass-to-light ratio (M/L) was ruled out for only 5 of the brighter galaxies, so these results are not broadly conclusive. There are a couple of other galaxies where extended stellar kinematics indicate a massive dark halo (Statler et al. 1999; Thomas et al. 2005). Note that with Λ CDM halos around elliptical galaxies, there should be no convenient “flat” part of the rotation curve where one can make a uniform Tully-Fisher measurement (as assumed in studies such as Ferrarese 2002).

In addition to G+01, there have been other approaches to deciphering the central DM content (Borriello et al. 2003; Padmanabhan et al. 2004; Trujillo et al. 2004; Mamon & Lokas 2005a; C+05). Almost all of them infer that DM is not dominant within R_{eff} , comprising $\sim 30\%$ of the mass as a typical estimate. Of particular interest is C+05, whose SAURON data and models are the best to date. Given their independent mass estimates from dynamics and stellar populations, we infer the DM fraction at a uniform physical radius, and compare these to theoretical predictions (see Fig. 1, right). The rotation-dominated galaxies are consistent with harboring dissipationless Λ CDM halos, while the anisotropy-dominated galaxies follow a trend expected for dissipative halo contraction (Blumenthal et al.

1986). However, a small systematic error could imply that the fast rotators have no DM at all, showing the limitations of working in the central regions only.

Modified Newtonian Dynamics (MOND) would explain these SAURON results with difficulty, requiring large *ad hoc* systematic errors. Also, the onset of mass discrepancies in ellipticals appears at higher accelerations than the universal MOND value (G+01). However, the uncertainties in this analysis are unclear.

3 Techniques and programs for large radius

Mass tracers well into the galactic halos are clearly needed. Two ubiquitous kinematical probes are planetary nebulae (PNe) and globular clusters (GCs). PNe are somewhat easier to observe in nearby galaxies, and importantly provide contiguous constraints with the central stellar kinematics. GCs are observable at larger distances and more abundant at larger radii. While ~ 1000 discrete velocities are normally required to fully constrain a hot dynamical system (Merritt & Saha 1993), in galaxies, many fewer are needed because of the additional strong constraints on the central regions provided by stellar kinematics.

There are so far a handful of galaxies with PN or GC kinematics measured (most are referenced in Napolitano et al. 05 = N+05). The largest PN study is of NGC 5128, with ~ 800 velocities (Peng et al. 2004). This peculiar galaxy shows evidence of a surprisingly weak DM halo, with $M/L_B \sim 13$ inside 80 kpc. The largest GC study is of NGC 1399, with ~ 700 velocities to 90 kpc (Richtler et al. 2004 and in prep). The constant GC velocity dispersion implies a massive DM halo as expected for this central Fornax Cluster galaxy.

Another halo probe is X-ray emitting hot gas. With the advent of *Chandra* and *XMM-Newton*, it is now possible in some galaxies to remove contaminating point sources, check the equilibrium of the gas, and determine the gas temperature profile (Fukazawa et al. 2006). However, the temptation of X-ray studies is to study the highest L_X systems, which gives a systematically biased picture of galaxy masses. It is important to control the selection effects.

Given the challenges of determining mass profiles, it is ideal to combine as many halo probes as possible, e.g. PNe, GCs, X-rays. The first exercise is to cross-check these for reliability (see Fig. 2, left). If they can all be used confidently, in combination the constraints are much stronger. E.g., one could derive the mass profile from X-rays and determine the orbit structures from kinematical data. Such a combined halo strategy is now underway. A long-term program with the PN.Spectrograph (PN.S; Douglas et al. 2002) is studying the PN kinematics. Various GC projects are underway at CTIO, Gemini, Magellan, and the VLT, as well as X-ray projects (O'Sullivan et al.) The framework of these surveys is to investigate the properties of *ordinary* elliptical galaxies ($\sim L^*$), as a function of environment, and comparing the two different families of boxy and disk galaxies (Kormendy & Bender 1996).

Dynamical interpretations of elliptical galaxies now often use the orbit modeling approach invented by Schwarzschild (1979) and extended by many others (see Thomas et al. 2005). Assuming a functional form for the gravitational potential,

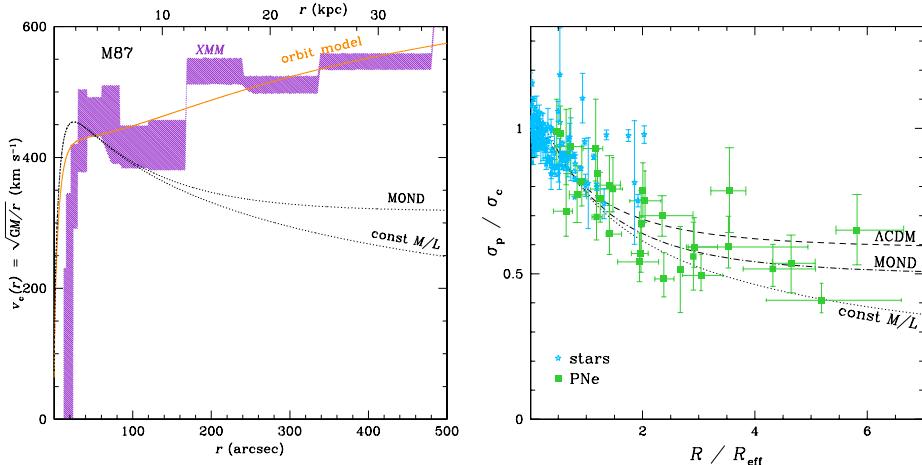


Fig. 2. *Left:* Modeled circular velocity profile of M87. Anisotropic orbit model uses stellar kinematics + 234 GC velocities. *XMM-Newton* model is from Matsushita et al. (2002). Dashed curves are isotropic models, showing that the GCs are near-isotropic, while the stars+PNe are not. *Right:* Projected velocity dispersion profiles, rescaled and stacked, of stars and PNe in 5 elliptical galaxies, compared to isotropic models.

one builds a comprehensive library of possible orbits. The contribution of each orbit to each observable is calculated, and the best-fitting orbit combination is found. Such methods (see also G+01) are physical by construction, and fully non-parametric in their orbit solutions. One can also make optimal use of the discrete velocities using maximum likelihood (Fig. 2, left: Romanowsky & Kochanek 2001; see also Wu & Tremaine 2005). Convergence issues can be addressed by attention to library size and regularization bias (Richstone et al. 2004).

4 First halo constraints on ordinary ellipticals

Five L^* ellipticals now have their PN halo kinematics measured (Méndez et al. 2001; Romanowsky et al. 2003; Teodorescu et al. 2005). Four of them show a similar decline in velocity dispersion with radius (Fig. 2, right), which is also seen in the Milky Way halo (Battaglia et al. 2005). While the decline is caused in part by the compact nature of the ellipticals' stellar mass distribution, it is still more extreme than expected from isotropic models with DM. However, isotropy is an arbitrary assumption, and there is an emerging consensus that radial orbits are expected in stellar halos (Sáiz et al. 2004; Dekel et al. 2005; Diemand et al. 2005; Abadi et al. 2005; but see González-García & Balcells 2005; Athanassoula 2005)—which could help produce the observed dispersions (Mamon & Lokas 2005b). More definitive mass determinations obviously require careful consideration of the anisotropy, which we have done for NGC 3379 as the first case.

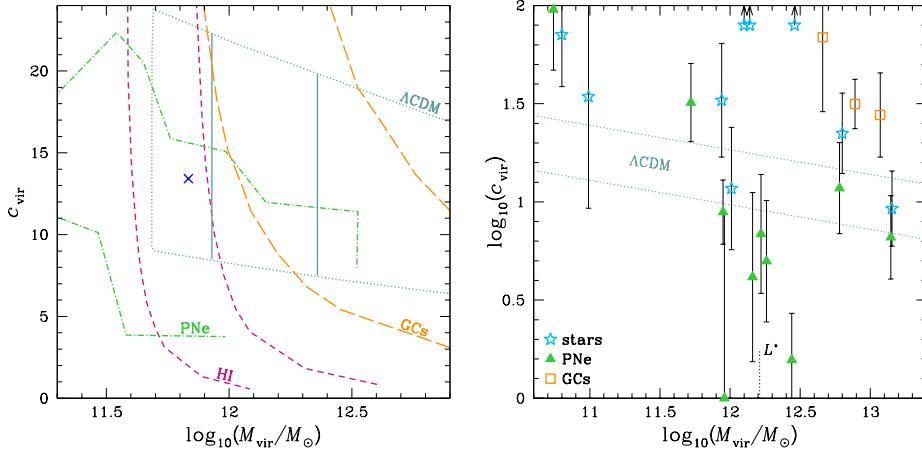


Fig. 3. Constraints on halo masses and concentrations. *Left:* NGC 3379, with various constraints shown as contours of 68%. For the Λ CDM boundaries, solid lines show predictions for a group or galaxy halo (van den Bosch et al. 2003), while dotted lines show the full range of physical plausibility. The best PNe+GCs+HI+ Λ CDM solution is marked by \times . *Right:* Results from a sample of early-type galaxies (after N+05).

For NGC 3379, we used spherical orbit models, with the constraints including stellar kinematics and 109 PN velocities. The best-fit models have an anisotropy parameter β varying from -0.3 in the center to $+0.5$ in the outer parts. The cumulative M/L_B at $5R_{\text{eff}}$ is 7.6 ± 0.9 , implying a DM fraction of 15–30% within this radius, which is surprisingly low. However, a typical Λ CDM halo is still allowed within the uncertainties (see Fig. 3, left). The situation may be clarified by the addition of the SAURON data and ~ 100 more PN velocities now obtained, along with refinements of the modeling.

There are other available constraints on the NGC 3379 halo. One is a HI-emitting gas ring in a near-Keplerian orbit at 100 kpc (Schneider 1985). The implied M/L_B is 27 ± 5 , startlingly low compared to expectations of ~ 150 for a group core (van den Bosch et al. 2003). We have also obtained 38 GC velocities to distances of 40 kpc (Bergond et al. 2006). These show a flat dispersion profile, indicating a more massive halo than the HI ring implies, and making a consensus solution between HI, PNe, and GCs difficult (see Fig. 3, left). Anisotropic GC models (with more velocities) are necessary to unravel this puzzle. Note that the PN and GC data are feasible with MOND, but the HI constraint is not.

5 Implications for Λ CDM and MOND

While firm results await full analyses of the PN.S (etc.) samples, in the meantime we can examine the available kinematical evidence on mass profiles. We have

assembled the literature data on the masses of ellipticals at $\geq 2R_{\text{eff}}$ (N+05). Assuming dissipationless Λ CDM halos, we make simple model fits for virial masses and concentrations (see Fig. 3, right). From these data and the results from central kinematics (Sec. 2), there is an emerging picture of a dichotomy in the DM distributions of faint/disky/rotating and bright/boxy/non-rotating ellipticals. The boxy galaxies appear DM-dominated, perhaps with strong dissipation-driven halo contraction, while the disky galaxies show weak DM, indicating halos that are less contracted or even nonexistent. Hints of this dichotomy have appeared elsewhere (Bertin et al. 1994; Magorrian & Ballantyne 2001; G+01; Ferreras et al. 2005), which seems opposite to what one expects in the picture of disky and boxy galaxies formed in gas-rich and gas-poor mergers, respectively (e.g. Naab et al. 2005).

There are a number of possible explanations for these results. One is that spherical modeling in some of the cases could systematically produce lower mass estimates. Another is that the halo concentrations are lower than expected because of baryonic physics (Mo & Mao 2004), or modified cosmological or dark matter models (McGaugh et al. 2003). Low halo concentrations have been suggested for late-type galaxies and for ellipticals (Rusin et al. 2003; Fukazawa et al. 2006).

Dekel et al. (2005) have shown that declining dispersion profiles may be the natural outcome of gas-rich galaxy mergers—produced by radial anisotropy, triaxiality, and perhaps by contamination with younger PNe. Whether their simulations include realistic baryonic physics and are representative of the full cosmological picture are open questions. But apart from this, their merger remnants may not resemble the real galaxies in question: e.g., the simulated dispersion decline is partially due to a high DM fraction in the central parts, while empirically the disky rotators appear to have low central DM content.

Such simulations are important because even if dynamical modeling of observed galaxies finds their mass distributions consistent with Λ CDM halos, this does not show that their overall structure and kinematics are predicted by Λ CDM. One may consider two complementary approaches to theory testing. The first is to fit the data with parametrized models (e.g. mass or anisotropy parameters), and see if the results are consistent with theory. Such model inferences will always include uncertain assumptions (about geometry, equilibrium, uniqueness, oversimplification). The second approach is to “observe” the theory, e.g. computing from simulations such observable quantities as $(v/\sigma)^*$ or the fundamental plane parameters. Special attention should be paid to the correlations between the observables. Both approaches need large samples of galaxies, observationally and theoretically, because of the intrinsic spread of galaxy properties.

With the advent of large samples of halo kinematics data, we can explore suitable parametrizations (as in the second approach). One possibility is the slope of the projected velocity dispersion profile. With simplified Λ CDM models (assuming isotropy, $R^{1/4}$ galaxies, no baryon contraction), the shape of the dispersion profile measured between 3 and 8 R_{eff} should be fairly independent of galaxy luminosity and insensitive to the scatter in galaxy and halo sizes. It is thus primarily sensitive to the overall DM fraction, and in Λ CDM the log-slope of the dispersion should be ~ -0.1 near L^* . The results available so far from PN kinematics do not compare

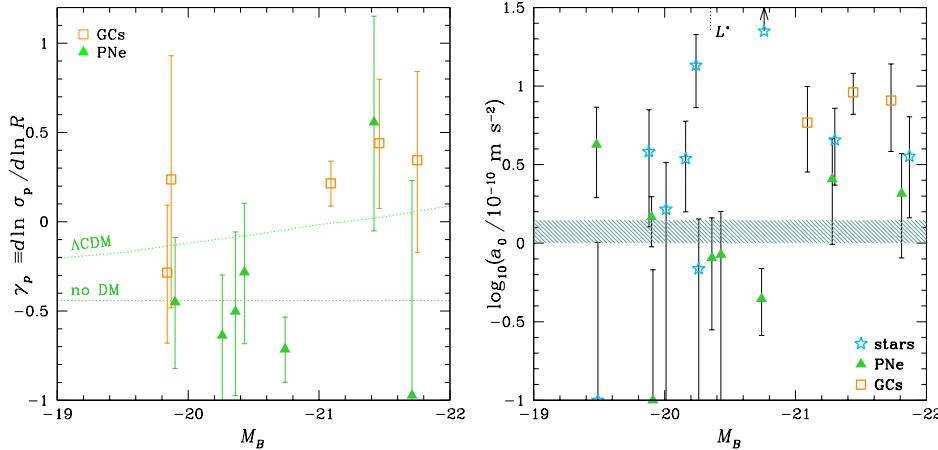


Fig. 4. *Left:* Log slope of projected velocity dispersion profiles, between 3 and 8 R_{eff} . Dotted lines show theoretical expectations for PNe, assuming isotropy. Points with error bars show observations. The GC data should not be compared directly to the PN models. *Right:* MOND acceleration parameter. The value implied by late-type galaxies is shown by a shaded region. Fits to halo kinematics are shown as points with error bars.

favorably with the predictions of this particular toy model (Fig. 4, left).

How does MOND shape up when compared to the data on ellipticals? We have taken the same literature data and found the best-fit acceleration parameter a_0 for each galaxy. The value of a_0 should be universal for all types of gravitational systems, and is found to be $\simeq (1.2 \pm 0.2) \times 10^{-10} \text{ m s}^{-2}$ in late-type galaxies. For the fainter ellipticals, this is consistent with most of the data (see Fig. 4, right, and Milgrom & Sanders 2003). For brighter galaxies, a higher value of a_0 is inferred, implying some DM is present even with MOND assumed; this is related to the problem of DM in cluster cores (Pointecouteau & Silk 2005). Another modified gravity theory has also been applied to ellipticals (Brownstein & Moffat 2006).

Thus, while the DM content of fainter ellipticals may be a hurdle for Λ CDM, the brighter ellipticals appear to be a roadblock for MOND. The situation should become steadily clearer with the combined program now underway on halo masses.

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